

ANTIPARTICLES AND ANTIMATTER: THE BASIC DIFFERENCE

Antonino Zichichi

CERN, Geneva, Switzerland

Enrico Fermi Centre, Rome, Italy

INFN and University of Bologna, Italy

Karlsruhe, 9 December 2008

«Those who say that antihydrogen is antimatter should realize that we are not made of hydrogen and we drink water, not liquid hydrogen».

These are Dirac's own words to a group of physicists (see Fig. 1) gathered around him, who, with a single equation [1], opened new horizons to human knowledge.



Figure 1: Dirac surrounded by young physicists in Erice, after a lecture when he explained the difference between antiparticles and antimatter. It is on this occasion that he made the statement reported at the beginning of this article.

To obtain water, hydrogen is not sufficient by itself. You also need oxygen whose nucleus is made of 8 protons and 8 neutrons.

Hydrogen is the only element in Mendeleev's Table to be constituted of two charged particles, the electron and the proton, without any role being played by the Nuclear Forces.

The first element on which Nuclear Forces come into play is the heavy hydrogen, whose nucleus, called deuteron, is made with one proton and one neutron. For these two particles to remain together the “nuclear glue” is needed.

Starting from the heavy hydrogen, all the elements of the Table, to exist, must have their nuclei made with protons, neutrons and the nuclear glue. If these last two ingredients, the neutron and the nuclear glue, were not available, nothing but the “light” hydrogen could exist. Farewell water and farewell all material which we are familiar with.

In Dirac's famous statement, 70 years of theoretical and experimental discoveries are taken into consideration, with the conclusion that the existence of antimatter is supported exclusively on an experimental basis.

In fact – as evidenced by T.D. Lee [2], – the CPT (Charge, Parity, Time) theorem is invalidated at the Planck Scale ($\cong 10^{19}$ GeV) where all Nature's Fundamental Forces converge. Since the Grand Unification is the source of everything, if CPT collapses at the energy level of the Grand Unification we can then bid farewell to all that derives from CPT.

A few words on the three Invariance operators of CPT. The first to be discovered was C: this tells us that the physical reality must remain invariable if we replace the charges additively conserved by their corresponding anticharges.

The first example was that of the electron and the antielectron. The C operator was discovered by H. Weyl in 1931 [3].

The operator P , discovered by Wigner, Wick and Wightman [4, 5], tells us that in replacing the right-handed systems by the left-handed

ones, the results of any fundamental experiment will not be changed.

The T operator, discovered by Wigner [6], Schwinger [7] and Bell [8] established that inverting the time axis will not alter the physical reality.

The mathematical formulation, designated by RQFT (*Relativistic Quantum Field Theory*) and supposed to be the basic description of Nature's Fundamental Forces, possesses the invariance property of CPT [9]: inverting all will not change the physical results.

Summarizing:

if we invert all the charges using C,
the three space reference axes (x y z)
using P and the time axis using T, all
remains as before.

Now, it is necessary to point out that matter is made of masses coupled to quantum numbers additively conserved (example: electric charges, leptonic numbers, baryonic numbers, “flavour” charges etc.). If we were to apply, to matter in a certain state, the three CPT operators we would obtain an antimatter state.

This means that the existence of matter, if the CPT theorem is valid, implies the existence of antimatter, and the mass of a piece of matter must be identical to that of the corresponding pieces of antimatter.

Let us suppose that Nature must obey the C invariance law. In this case, the existence of matter implies the existence of antimatter. If, however, the C invariance is broken, the existence of antimatter is guaranteed by CPT.

Let us suppose that CP is valid. Again in this case, the existence of matter dictates the existence of antimatter. If, however, CP is not valid, the existence of antimatter is guaranteed by CPT. If, however, CPT collapses, then only experimental physics can guarantee the existence of antimatter.

This is the synthesis of what effectively happened during the decades since Dirac, in 1928, came up with his equation, until we finally understood that CPT was not that basic invariance governing all the Fundamental Forces of Nature.

And now, a brief review of the facts.

Three years after Dirac came up with his equation, H. Weyl discovered C and it was thought at the time that the existence of the antielectron [10] and the production of electron–antielectron pairs [11] were the consequences of C invariance.

There was also the equality between the mean life of positive and negative muons

$$\tau_{\mu^+} = \tau_{\mu^-}$$

which was thought to be an unavoidable consequence of the validity of C.

It continued with the discoveries of the antiproton [12], of the antineutron [13] and, finally of the strange meson called θ_2^0 [14].

This apparent triumph of the Invariance Operators went in parallel with the success in identifying a “point-like” mathematical formulation,

capable of describing the Fundamental Forces of Nature.

Starting with the four Maxwell equations and carrying it further, a marvellous construction was finally achieved, one which we have already mentioned: the RQFT.

This formulation should have been able to describe not only the electromagnetic forces (from which it was derived) but also the Weak and Nuclear Forces.

What reinforced these convictions were two great achievements.

The first mathematical formulation of the Weak Forces by Fermi and the Yukawa triumph [15] with the discovery of the “nuclear glue”, – the famous π meson – thanks to Lattes, Muirhead, Occhialini and Powell [15].

However, these initial extraordinary successes were later confronted with enormous difficulties.

In QED, the so-called “Landau poles” and the conclusion that the fundamental “bare” electric charge had to be zero; in the Weak Forces, at the energy level of 300 GeV, unitarity fell apart; in the Nuclear Forces, the enormous proliferation of baryons and mesons which was totally out of our understanding in terms of RQFT.

And this is how a mathematical formulation, the so called “Scattering Matrix”, designated by S-Matrix, was brought in, which was the total negation of the “field” concept. For its existence, three conditions were needed: analyticity, unitarity and crossing. Why bother with RQFT if S-Matrix is enough?

But, if RQFT does not exist, how do we cope with the existence of CPT invariance? This opened another field: that related to the breaking of the invariance laws, C, P, T.

Dalitz, in 1953 [16], came up with the famous (θ – τ) puzzle: two mesons, with identical properties, had to be of opposite parity.

Intrigued by this “puzzle”,
Lee and Yang [17]
analysed the experimental results of
the Weak Forces and
discovered
that there was no proof confirming the
validity of C and P in the Weak
Interactions.

Within one year of their findings, C.S.Wu [18], discovered that the invariance laws of C and P were violated in the Weak Interactions. How do we then cope with the existence of antimatter? This is why Landau [19] came up with his idea: if both the C and P operators are violated, their product, CP, may be conserved.

The existence of antimatter is guaranteed by the validity of CP.

We thus reach 1964,
and the discovery of the CP violation
in the decay of the neutral strange
mesons [20].

Now, there is a small detail which
was always overlooked.

In 1957, before the experimental discovery of the C and P violations, in a paper which not many had read (or understood),

Lee, Oehme and Yang [21] demonstrated that, contrary to what had been said and repeated, the existence of the two neutral strange mesons, θ_1 and θ_2 [14], was not a proof of the validity of either C, P or of their product CP.

The CP breaking involves that of T, if we want the CPT product to remain conserved.

For some of the founding fathers of modern physics, the invariance relative to the time inversion, at the level of the Fundamental Laws,
had to remain untouched.

Therefore, if CP breaks and T doesn't, CPT must break.

And, after all, why not?

In actual fact, the basis of CPT was RQFT, but now, it seemed as if this mathematical formulation had to be replaced by the S-Matrix.

The breaking of the Invariance Operators (C, P, CP) and the apparent triumph of the S-Matrix were coupled to

experimental results which indicated that there was no trace of antideuteron, even after producing ten million pions.

I was in Dubna, in 1964, when Jim Cronin presented the results on CP violation obtained together with Fitch, Christenson and Turley [20].

On my right I had Bruno Touschek and on my left Bruno Pontecorvo.

Both told me then “*they have ruined their reputation*”.

The validity of CP, with antimatter as the mirror image of matter, proposed by Landau, held a lot of attraction. To put in doubt the CP invariance had very few believers.

However Dirac was one of these and he fell into a spell of deep “scientific depression”.

He, who was well known for his caution, had total belief in the C invariance, which brought him to predict the existence of antiparticles, antimatter, antistars and antigalaxies. And now even CP was *breaking*. To obtain the theoretical prediction for the existence of antimatter CPT had to be valid, which meant violation of T.

No one could imagine, back in 1964, that physics would open the new horizons that we know today. The only actions, left to us, were of a technological-experimental nature. In fact, the discovery of antimatter required the realization of the most powerful beam of negative particles in the Protosynchrotron (PS) of CERN,

and the invention of a new technology capable of measuring, with a precision never achieved before, the time-of-flight of charged particles. This is how we came to discover that an antideuteron was produced not after **ten million** but after a **hundred million** pions [22].

Dirac came out of his depression when he received a phone call from his friend Abdus Salam, saying «*Relax Paul, my friend Nino Zichichi has discovered the antideuteron*». Dirac called me and invited me for lunch at his place, and this is how we started a friendship which led us to the realization of the Erice Seminars on Nuclear Wars. The letter written by Mrs Dirac recalling this event is reported in Fig. 2.

Professor Antonino ZICHICHI
University of Bologna and
Bologna Academy of Science
Via Zamboni 31
40126 BOLOGNA, Italy

Tallahassee, 16 December 1995

Dear Nino,

on the occasion of the International Symposium in your honour, to celebrate the 30th Anniversary of the Discovery of Nuclear Antimatter, let me recall the joy that I saw in Paul's eyes when he received the phone call from his friend Abdus Salam, telling him that the first example of nuclear antimatter had been discovered at CERN by Nino Zichichi.

This is how we got to know each other : I still remember your first visit to us. I had prepared a typical hungarian cake. Do you remember how much did you eat of it and enjoyed it because it was like the pastry of your native country, Sicily?

That was a great evening for Paul and me because it was the beginning of an unforgettable friendship that brought to many interesting results, like the Erice Seminars on Nuclear Wars. Paul was very proud of his activity in Erice for Peace and Freedom when the world was separated by the iron curtain.

I wish I could be in Bologna but I remind you that you have promised me to be here in Tallahassee soon.

With lots of love to you and Maria Ludovica.

Yours,



Figure 2: The letter by Mrs Mancy Dirac.

Let me say a few words on the experiment. The search for the existence of the first example of nuclear antimatter needed a high intensity beam of negative particles produced in high energy interactions. This negative beam was dominated by pions, with a fraction of K mesons and few antiprotons.

It was necessary
to separate negative particles
with different masses,
starting with the very light pions and
then going up with mass to
K mesons, antiprotons
and (hopefully) antideuteron.

To accomplish this, the first step was a combined system of bending magnets (BM) coupled with magnetic quadrupoles (Q), for focusing purposes, and a strong electrostatic field (Separator). The sequence of all these elements is shown in Fig. 3.

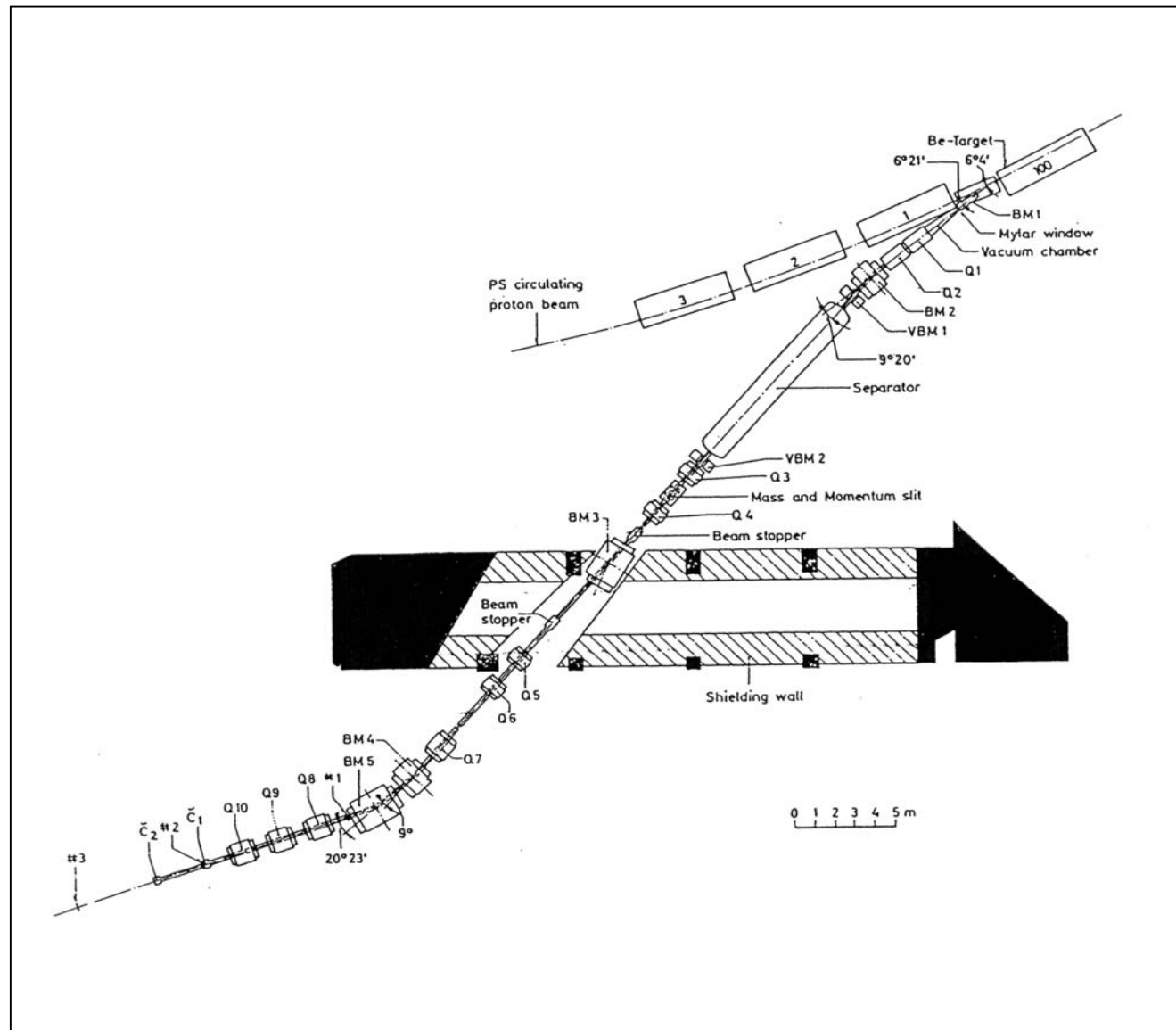


Figure 3a: Schematic layout of the experimental set-up that allowed the discovery of antimatter.

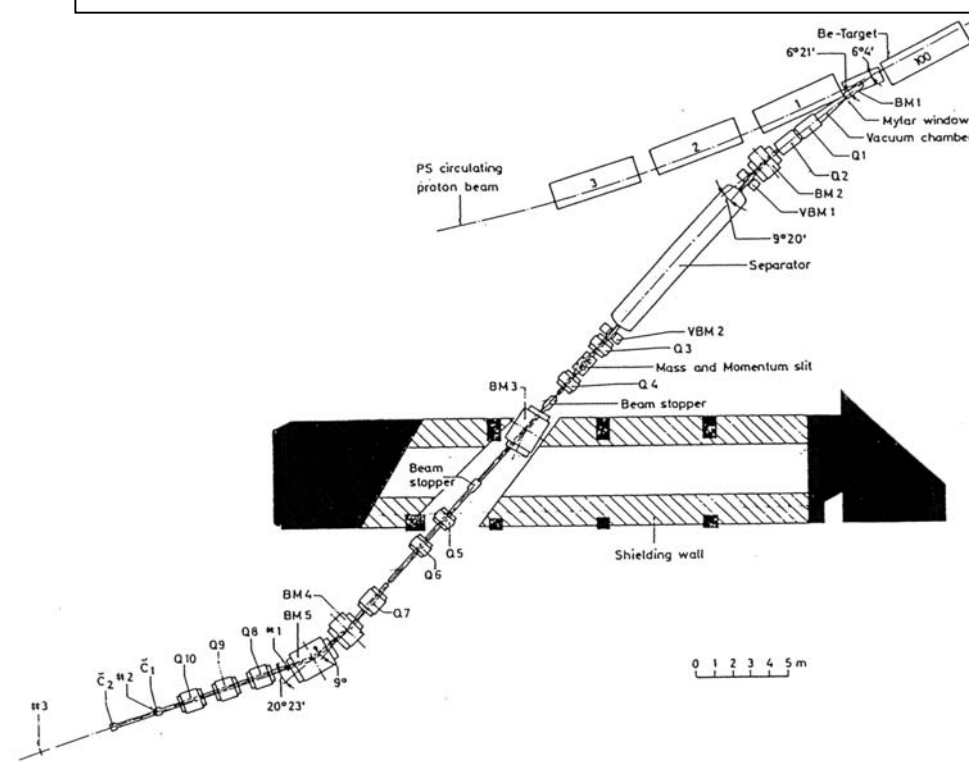
This very high intensity beam of negative “partially separated” particles was the result of

a special project,
made and carried out with two friends
of mine:

Mario Morpurgo and Guido Petrucci.

The second vital step was a very sophisticated time-of-flight (TOF) system able to achieve the time resolution needed in order to detect a negative particle (the antideuteron) in a background of one hundred million of other negative particles (essentially π mesons).

$$\text{TOF} \equiv \pm 75 \text{ psec}$$



The most intense negative beam ever built with the details of the mass-spectrometer to search for **antideuteron**s [22] and the high precision TOF system.

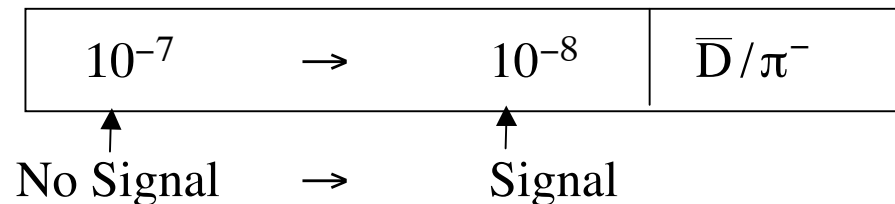
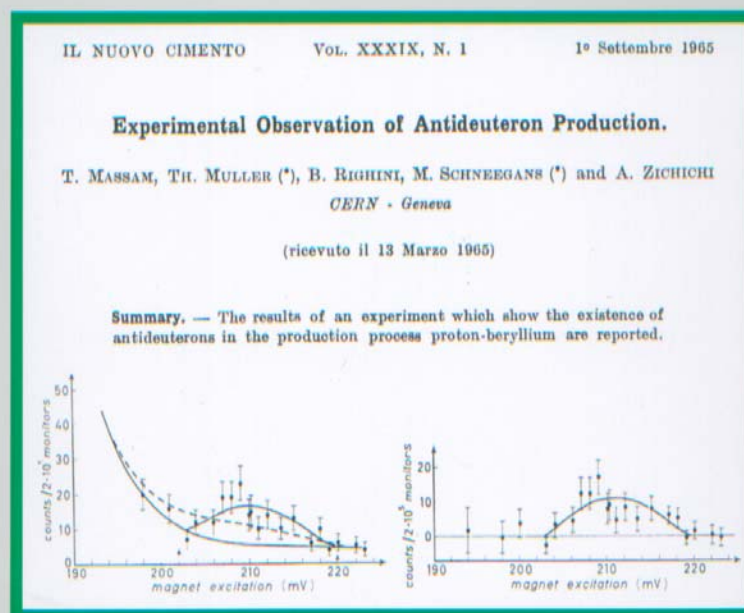


Figure 3b.

The results are shown in Fig. 4
where the existence
of a negative particle
with the mass
equal to that of the deuteron
is reported.

THE DISCOVERY OF NUCLEAR ANTIMATTER

Edited by L. Maiani and R. A. Ricci



«I think that this discovery of antimatter was perhaps the biggest jump of all the big jumps in physics in our century»

Werner Heisenberg

Figure 4: Front cover of the book celebrating the 30th anniversary of the antideuteron discovery.

The other Figures (5-10) refer to physicists who have been engaged in the physics of symmetry operators and of their breaking, starting with Paul Dirac and Eugene P. Wigner (Fig. 5), John S. Bell (Fig. 6), Richard R. Dalitz (Fig. 7), C.S. Wu (Fig. 8), Val L. Fitch (Fig. 9) and T.D. Lee (Fig. 10).



Figure 5: Eugene P. Wigner, A. Zichichi and Paul Dirac (Erice, 1982).



Figure 6: John S. Bell (Erice, 1963).



Figure 7: Richard R. Dalitz in Erice (June 1990).



Figure 8: M.me Wu in Erice (1994).



Figure 9: From right in the picture: Val L. Fitch, Sheldon L. Glashow, A. Zichichi awarding the “Best Student” prize of the Subnuclear Physics School (Erice, 1981).

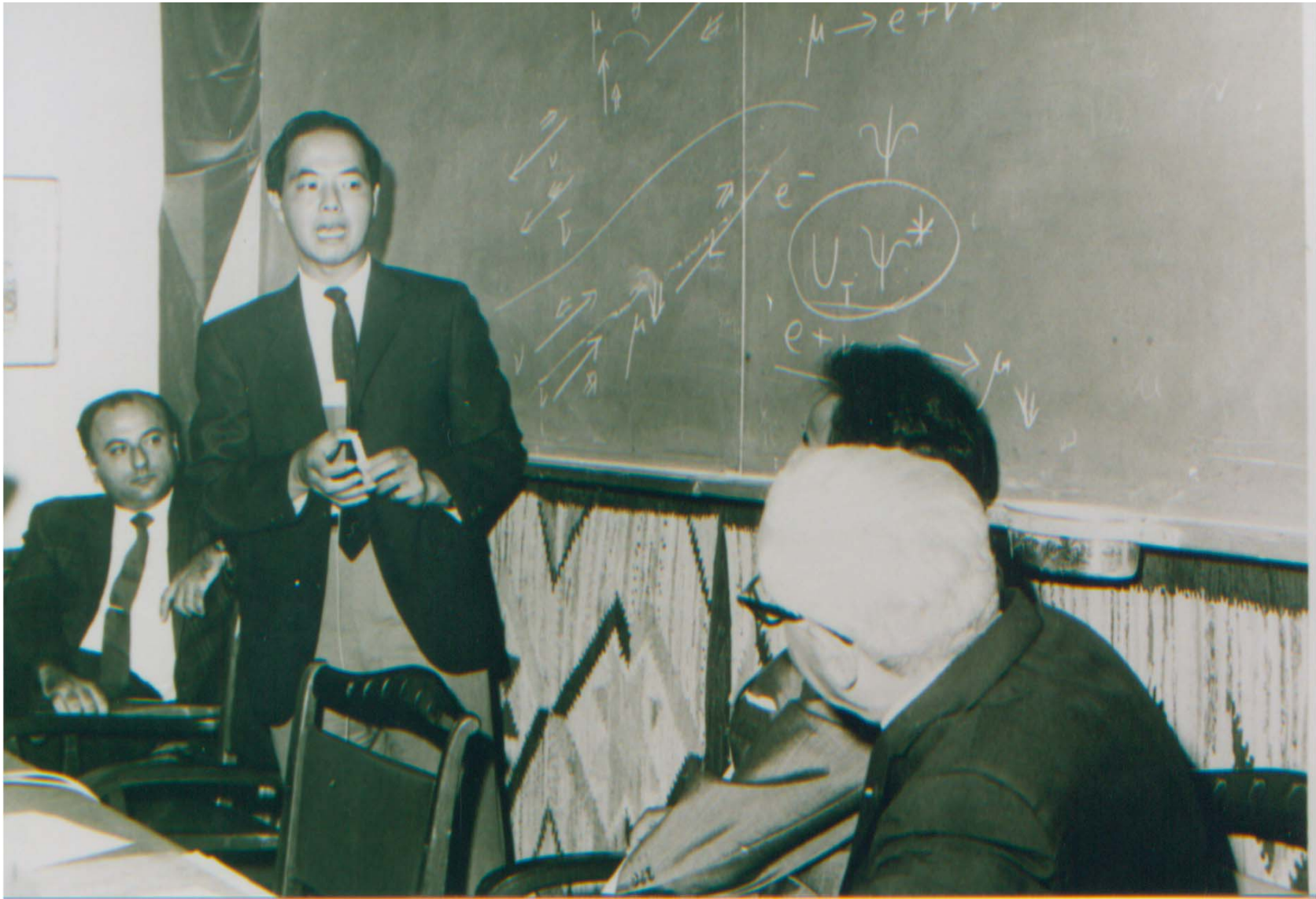


Figure 10: T.D. Lee explaining why the CPT theorem collapses at the Planck Scale (Melvin Schwartz on the left, Isidor I. Rabi last on the right of the picture).

And now, back to the antideuteron. To understand the importance of this discovery we need to have a clear idea of what is meant by matter. The Particles are not sufficient to constitute matter, we also need the glue. Using that of electromagnetism, we can constitute atoms and molecules.

To constitute the nucleus, we need protons, neutrons and nuclear glue.

It's similar with bricks.

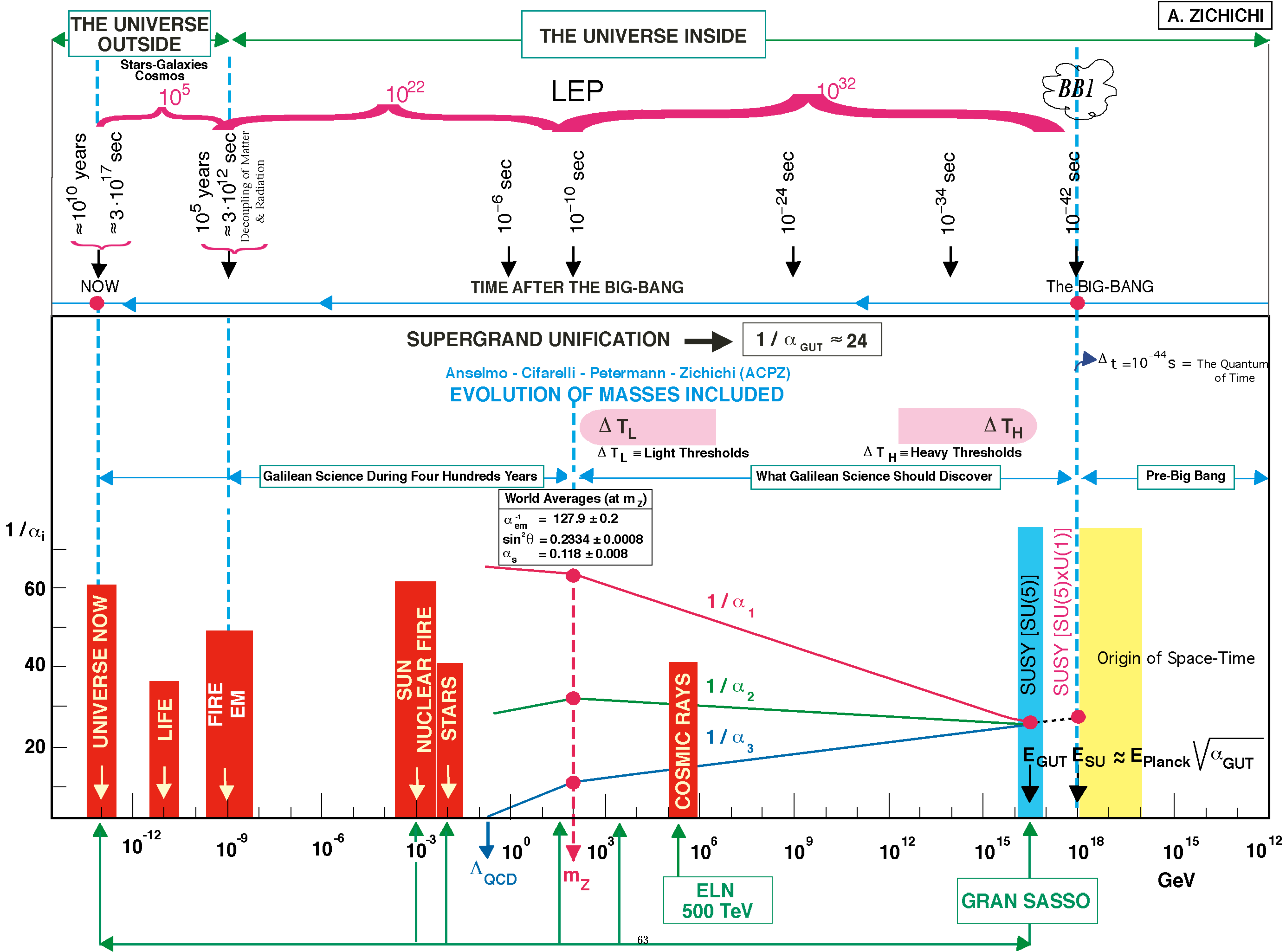
To build a house we need “glues”, for bricks alone are not enough. Matter corresponds to the house and not to the bricks alone.

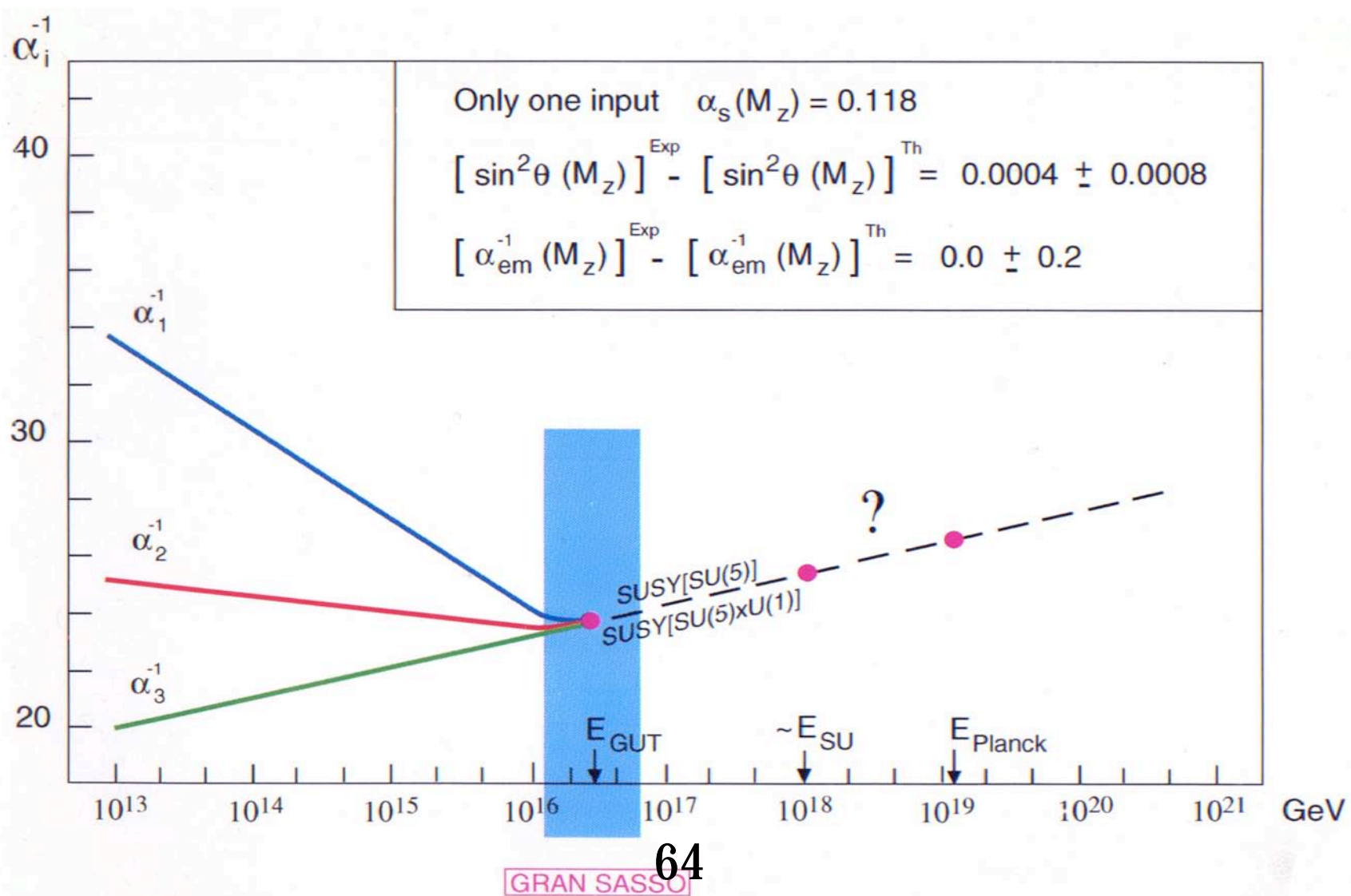
If, thanks to well determined laws,
we know that

bricks and antibricks exist,
all that can be achieved is to have piles
of bricks and piles of antibricks.
Not houses and antihouses.

If the world where we live tells us that houses exist, to ascertain that antihouses also exist we must formulate a law that establishes the existence of antiglues, exactly identical to the glues that allow the joining of bricks to build houses.

We know today that
all the Fundamental Forces
converge
at the Planck Energy
where
CPT invariance breaks down.





On the other hand, CPT results from the point-like mathematical formulation called RQFT, but CPT collapses at the energy level from which the fundamental forces originate, i.e. at the Planck Energy. If we replace the “point” by the “string” the *Relativistic Quantum String Theory* RQST comes out. However, this RQST does not have CPT invariance.

This means that
no theory exists
which can guarantee that, if we have
“houses”, then “antihouses” must exist.
This is why the fact that
all antiatoms with their antinuclei must
exist is based on the
CERN experiment [22] of March 1965.

SUMMARY

**THE INCREDIBLE SERIES OF UEEC EVENTS
NEEDED TO EXPLAIN THE STABILITY OF MATTER
SEVEN DECADES: FROM THE ANTIELECTRON TO ANTIMATTER
AND THE UNIFICATION OF ALL GAUGE FORCES**

• **The validity of C invariance from 1927 to 1957.**

After the discovery by Thomson in 1897 of the first example of an elementary particle, the Electron, it took the genius of Dirac to theoretically discover the Antielectron thirty years after Thomson.

- 1927** → Dirac equation [19]; the existence of the antielectron is, soon after, theoretically predicted. Only a few years were needed, after Dirac's theoretical discovery, to experimentally confirm (Anderson, Blackett and Occhialini [20]) the existence of the Dirac antielectron.
- 1930-1957** → **Discovery of the C operator** [(charge conjugation) H. Weyl and P.A.M. Dirac [21]]; discovery of the P Symmetry Operator [E.P. Wigner, G.C. Wick and A.S. Wightman [22, 23]]; discovery of the T operator (time reversal) [E.P. Wigner, J. Schwinger and J.S. Bell [24, 25, 26, 27]]; discovery of the CPT Symmetry Operator from RQFT (1955-57) [28].
- 1927-1957** → Validity of C invariance: e^+ [20]; \bar{p} [29]; \bar{n} [30]; $K_S^0 \rightarrow 3\pi$ [31] but see LOY [32].

• **The new era starts: $C \neq$; $P \neq$; $CP \neq$ (*) .**

- 1956** → Lee & Yang $P \neq$; $C \neq$ [33].
- 1957** → Before the experimental discovery of $P \neq$ & $C \neq$, Lee, Oehme, Yang (LOY) [32] point out that the existence of the second neutral K-meson, $K_S^0 \rightarrow 3\pi$, is proof neither of C invariance nor of CP invariance. Flavour antiflavour mixing does not imply CP invariance.
- 1957** → C.S. Wu et al. $P \neq$; $C \neq$ [34]; CP ok [35].
- 1964** → $K_S^0 \rightarrow 2\pi \equiv K_L$: CP \neq [36].
- 1947-1967** → QED divergences & Landau poles.
- 1950-1970** → The crisis of RQFT & the triumph of S-matrix theory (i.e. the negation of RQFT).
- 1965** → Nuclear antimatter is (experimentally) discovered [37]. See also [38].
- 1968** → The discovery [39] at SLAC of Scaling (free quarks inside a nucleon at very high q^2) but in violent (pp) collisions no free quarks at the ISR are experimentally found [40]. Theorists consider Scaling as being evidence for RQFT not to be able to describe the Physics of Strong Interactions. The only exception is G. 't Hooft who discovers in 1971 that the β -function has negative sign for non-Abelian theories [41].
- 1971-1973** → $\beta = -$; 't Hooft; Politzer; Gross & Wilczek. The discovery of **non-Abelian** gauge theories. Asymptotic freedom in the interaction between quarks and gluons [41].
- 1974** → All gauge couplings $\alpha_1 \alpha_2 \alpha_3$ run with q^2 but they do not converge towards a unique point.
- 1979** → A.P. & A.Z. point out that the new degree of freedom due to SUSY allows the three couplings $\alpha_1 \alpha_2 \alpha_3$, **to converge towards a unique point** [42].
- 1980** → QCD has a 'hidden' side: the multitude of final states for each pair of interacting particles: (e^+e^- ; $p\bar{p}$; πp ; Kp ; νp ; pp ; etc.) The introduction of the Effective Energy allows to discover the Universality properties [43] in the multihadronic final states.
- 1992** → All gauge couplings converge towards a unique point at the gauge unification energy: $E_{GU} \approx 10^{16}$ GeV with $\alpha_{GU} \approx 1/24$ [44, 45] .
- 1994** → The Gap [4] between E_{GU} & the String Unification Energy: $E_{SU} \approx E_{Planck}$.
- 1995** → **CPT loses its foundations at the Planck scale (T.D. Lee)** [46].
- 1995-1999** → **No CPT theorem from M-theory (B. Greene)** [47].
- 1995-2000** → A.Z. points out the need for new experiments to establish if matter-antimatter symmetry or asymmetry are at work.

(*) The symbol \neq stands for 'Symmetry Breakdown'.

THE INCREDIBLE SERIES OF UEEC EVENTS
NEEDED TO EXPLAIN THE STABILITY OF MATTER
SEVEN DECADES: FROM THE ANTIELECTRON TO ANTIMATTER
AND THE UNIFICATION OF ALL GAUGE FORCES

- **The validity of C invariance from 1927 to 1957.**

After the discovery by Thomson in 1897 of the first example of an elementary particle, the Electron, it took the genius of Dirac to theoretically discover the Antielectron thirty years after Thomson.

1927 → Dirac equation [19]; the existence of the antielectron is, soon after, theoretically predicted. Only a few years were needed, after Dirac's theoretical discovery, to experimentally confirm (Anderson, Blackett and Occhialini [20]) the existence of the Dirac antielectron.

1930-1957 → **Discovery of the C operator** [(charge conjugation) H. Weyl and P.A.M. Dirac [21]]; discovery of the P Symmetry Operator [E.P. Wigner, G.C. Wick and A.S. Wightman [22, 23]]; discovery of the T operator (time reversal) [E.P. Wigner, J. Schwinger and J.S. Bell [24, 25, 26, 27]]; discovery of the CPT Symmetry Operator from RQFT (1955-57) [28].

1927-1957 → Validity of C invariance: e^+ [20]; \bar{p} [29]; \bar{n} [30]; $K_2^0 \rightarrow 3\pi$ [31] but see LOY [32].

• **The new era starts: $C \neq$; $P \neq$; $CP \neq$ (*) .**

1956 → Lee & Yang $P \neq$; $C \neq$ [33].

1957 → Before the experimental discovery of $P \neq$ & $C \neq$, Lee, Oehme, Yang (LOY) [32] point out that the existence of the second neutral K-meson, K_2^0 → 3π , is proof neither of C invariance nor of CP invariance. Flavour antiflavour mixing does not imply CP invariance.

1957 → C.S. Wu et al. $P \neq$; $C \neq$ [34]; CP ok [35].

1964 → $K_2^0 \rightarrow 2\pi \equiv K_L$: $CP \neq$ [36].

1947-1967 → QED divergences & Landau poles.

1950-1970 → The crisis of RQFT & the triumph of S-matrix theory (i.e. the negation of RQFT).

1965 → Nuclear antimatter is (experimentally) discovered [37]. See also [38].

1968 → The discovery [39] at SLAC of Scaling (free quarks inside a nucleon at very high q^2) but in violent (pp) collisions no free quarks at the ISR are experimentally found [40]. Theorists consider Scaling as being evidence for RQFT not to be able to describe the Physics of Strong Interactions. The only exception is G. 't Hooft who discovers in 1971 that the β -function has negative sign for non-Abelian theories [41].

- 1971-1973** → $\beta = -$; 't Hooft; Politzer; Gross & Wilczek. The discovery of **non-Abelian** gauge theories. Asymptotic freedom in the interaction between quarks and gluons [41].
- 1974** → All gauge couplings α_1 α_2 α_3 run with q^2 but they do not converge towards a unique point.
- 1979** → A.P. & A.Z. point out that the new degree of freedom due to SUSY allows the three couplings α_1 α_2 α_3 , **to converge towards a unique point** [42].
- 1980** → QCD has a 'hidden' side: the multitude of final states for each pair of interacting particles: (e^+e^- ; $p\bar{p}$; πp ; Kp ; νp ; pp ; etc.)
The introduction of the Effective Energy allows to discover the Universality properties [43] in the multihadronic final states.
- 1992** → All gauge couplings converge towards a unique point at the gauge unification energy: $E_{GU} \cong 10^{16}$ GeV with $\alpha_{GU} \cong 1/24$ [44, 45] .
- 1994** → The Gap [4] between E_{GU} & the String Unification Energy: $E_{SU} \cong E_{Planck}$.
- 1995** → **CPT loses its foundations at the Planck scale (T.D. Lee)** [46].
- 1995-1999** → **No CPT theorem from M-theory (B. Greene)** [47].
- 1995-2000** → A.Z. points out the need for new experiments to establish if matter-antimatter symmetry or asymmetry are at work.

CONSTITUENTS AND ANTICONSTITUENTS

FUNDAMENTAL FERMIONS AND ANTIFERMIONS

Leptons (ℓ)

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_{HL} \\ HL \\ \tau \end{pmatrix}$$

Antileptons ($\bar{\ell}$)

and

Quarks (q)

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

Antiquarks (\bar{q})

PARTICLES

Mesons and Baryons

$$(q\bar{q}) \qquad (qqq)$$

and

ANTIPARTICLES

Antimesons and Antibaryons

$$(\bar{q}q) \qquad (\bar{q}\bar{q}\bar{q})$$

NUCLEI AND ANTINUCLEI

$$\begin{aligned} (pn) &= D & ; & & (\bar{p}\bar{n}) &= \bar{D} \\ (pnn) &= {}^3\text{H} & ; & & (\bar{p}\bar{n}\bar{n}) &= {}^3\bar{\text{H}} \\ (ppn) &= {}^3\text{He} & ; & & (\bar{p}\bar{p}\bar{n}) &= {}^3\bar{\text{He}} \end{aligned}$$

CONSTITUENTS AND ANTICONSTITUENTS


FUNDAMENTAL FERMIONS AND ANTIFERMIONS

Leptons (ℓ)

and

Quarks (q)

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_{HL} \\ HL \end{pmatrix} \quad ;$$



$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

Antileptons ($\bar{\ell}$)

and

Antiquarks (\bar{q})

PARTICLES

Mesons and Baryons

$(q \bar{q})$

(qqq)

and

ANTIPARTICLES

Antimesons and Antibaryons

$(\bar{q}q)$

$(\bar{q}\bar{q}\bar{q})$

NUCLEI

AND

ANTINUCLEI

(pn) \equiv D

;

($\overline{p}\overline{n}$) \equiv \overline{D}

(pnn) \equiv ^3H

;

($\overline{p}\overline{n}\overline{n}$) \equiv $^3\overline{\text{H}}$

(ppn) \equiv ^3He

;

($\overline{p}\overline{p}\overline{n}$) \equiv $^3\overline{\text{He}}$

HOW MATTER IS BUILT		MASSSES	HOW ANTIMATTER IS BUILT	
FUNDAMENTAL FERMIONS	NEEDED FOR ORDINARY MATTER	<i>Intrinsic</i>	NEEDED FOR ORDINARY ANTIMATTER	FUNDAMENTAL ANTIFERMIONS
$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_{HL} \\ HL^- \end{pmatrix} \text{ Leptons}$ \uparrow_{τ^-} $\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \text{ Quarks}$	$\Rightarrow e^-$ $\Rightarrow \begin{pmatrix} u \\ d \end{pmatrix}$		$e^+ \Leftarrow \begin{pmatrix} \bar{\nu}_e \\ e^+ \end{pmatrix} \begin{pmatrix} \bar{\nu}_\mu \\ \mu^+ \end{pmatrix} \begin{pmatrix} \bar{\nu}_{HL} \\ HL^+ \end{pmatrix} \text{ Antileptons}$ \uparrow_{τ^+} $\begin{pmatrix} \bar{u} \\ \bar{d} \end{pmatrix} \Leftarrow \begin{pmatrix} \bar{u} \\ \bar{d} \end{pmatrix} \begin{pmatrix} \bar{c} \\ \bar{s} \end{pmatrix} \begin{pmatrix} \bar{t} \\ \bar{b} \end{pmatrix} \text{ Antiquarks}$	
PARTICLES		<i>Intrinsic & Confinement</i>		ANTIPARTICLES
Mesons ($q\bar{q}$) $\Rightarrow \pi_0^\pm$ Baryons (qqq) $\Rightarrow \begin{pmatrix} p \\ n \end{pmatrix}$			$\pi_0^\pm \Leftarrow$ $\begin{pmatrix} \bar{p} \\ \bar{n} \end{pmatrix} \Leftarrow$ Antimesons ($\bar{q}q$) Antibaryons ($\bar{q}\bar{q}\bar{q}$)	
NUCLEI		<i>Intrinsic & Confinement & Nuclear Binding</i>		ANTINUCLEI
$(pn) \equiv D$ $(pnn) \equiv {}^3H$ $(ppn) \equiv {}^3H_c$ $(ppnn) \equiv H_c$	All Nuclei up to the element with 118 protons and 175 neutrons contribute to fill the Mendeleev table		All Antinuclei up to the element with 118 antiprotons and 175 antineutrons contribute to fill the Mendeleev table	$(\bar{p}\bar{n}) \equiv \bar{D}$ $(\bar{p}\bar{n}\bar{n}) \equiv {}^3\bar{H}$ $(\bar{p}\bar{p}\bar{n}) \equiv {}^3\bar{H}_c$ $(\bar{p}\bar{p}\bar{n}\bar{n}) \equiv {}^4\bar{H}_c$
ATOMS		<i>Intrinsic & Confinement & EM Binding</i>		ANTIATOMS
The simplest Atom	Hydrogen $\equiv (p e^-)$		Antihydrogen $\equiv (\bar{p} e^+)$	The simplest AntiAtom
ALL OTHER ATOMS	Nuclei & Electrons Deuterium: $[(pn) e^-]$ Helium: $[(ppnn) e^- e^-]$ etc.	<i>Intrinsic & Confinement & EM Binding & Nuclear Binding</i>	Antinuclei & Positrons Antideuterium: $[(\bar{p}\bar{n}) e^+]$ Antihelium: $[(\bar{p}\bar{p}\bar{n}\bar{n}) e^+ e^+]$ etc. ...	ALL OTHER ANTIATOMS

HOW MATTER IS BUILT		MASSES	HOW ANTIMATTER IS BUILT	
FUNDAMENTAL FERMIONS	NEEDED FOR ORDINARY MATTER	<i>Intrinsic</i>	NEEDED FOR ORDINARY ANTIMATTER	FUNDAMENTAL ANTIFERMIONS
$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_{HL} \\ HL^- \end{pmatrix} \text{ Leptons}$ $\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \text{ Quarks}$	$\Rightarrow e^-$ $\Rightarrow \begin{pmatrix} u \\ d \end{pmatrix}$		$e^+ \Leftarrow \begin{pmatrix} \bar{\nu}_e \\ e^+ \end{pmatrix} \begin{pmatrix} \bar{\nu}_\mu \\ \mu^+ \end{pmatrix} \begin{pmatrix} \bar{\nu}_{HL} \\ HL^+ \end{pmatrix} \text{ Antileptons}$ $\begin{pmatrix} \bar{u} \\ \bar{d} \end{pmatrix} \Leftarrow \begin{pmatrix} \bar{u} \\ \bar{d} \end{pmatrix} \begin{pmatrix} \bar{c} \\ \bar{s} \end{pmatrix} \begin{pmatrix} \bar{t} \\ \bar{b} \end{pmatrix} \text{ Antiquarks}$	
PARTICLES		<i>Intrinsic & Confinement</i>		ANTIPARTICLES
Mesons ($q\bar{q}$) Baryons (qqq)	$\Rightarrow \pi_0^\pm$ $\Rightarrow \begin{pmatrix} p \\ n \end{pmatrix}$		$\pi_0^\pm \Leftarrow$ $\begin{pmatrix} \bar{p} \\ \bar{n} \end{pmatrix} \Leftarrow$	Antimesons ($\bar{q}q$) Antibaryons ($\bar{q}\bar{q}\bar{q}$)
NUCLEI		<i>Intrinsic & Confinement & Nuclear Binding</i>		ANTINUCLEI
$(pn) \equiv D$ $(pnn) \equiv {}^3H$ $(ppn) \equiv {}^3H_c$ $(pppn) \equiv H_c$	All Nuclei up to the element with 118 protons and 175 neutrons contribute to fill the Mendelev table		All Antinuclei up to the element with 118 antiprotons and 175 antineutrons contribute to fill the Mendelev table	$(\bar{p}\bar{n}) \equiv \bar{D}$ $(\bar{p}\bar{n}\bar{n}) \equiv {}^3\bar{H}$ $(\bar{p}\bar{p}\bar{n}) \equiv {}^3\bar{H}_c$ $(\bar{p}\bar{p}\bar{n}\bar{n}) \equiv {}^4\bar{H}_c$

<div>ATOMS</div>				<div>ANTIATOMS</div>
<p>The simplest Atom</p>	<p>Hydrogen $\equiv (p\ e^-)$</p>	<p><i>Intrinsic & Confinement & EM Binding</i></p>	<p>Antihydrogen $\equiv (\bar{p}\ e^+)$</p>	<p>The simplest AntiAtom</p>
<p>ALL OTHER ATOMS</p>	<p>Nuclei & Electrons Deuterium: $[(pn)\ e^-]$ Helium: $[(ppnn)\ e^-e^-]$ etc.</p>	<p><i>Intrinsic & Confinement & EM Binding & Nuclear Binding</i></p>	<p>Antinuclei & Positrons Antideuterium: $[(\bar{p}\bar{n})\ e^+]$ Antihelium: $[(\bar{p}\bar{p}\bar{n}\bar{n})\ e^+e^+]$ etc. ...</p>	<p>ALL OTHER ANTIATOMS</p>

Table 3: If the Hydrogen atom were the only element in the Mendeleev table, then the only form of antimatter would be the anti-Hydrogen atom. There are, by now, 118 elements in the Mendeleev table and the first element, Hydrogen, is the only example of atom made of two elementary particles: the proton and the electron. In order for (what we call) matter to exist, it is necessary that protons and neutrons can attract each other to form nuclei.

FROM FERMI-DIRAC TO NOW

1927

P.A.M. DIRAC

$$(i\not{\partial} + m)\psi = 0$$

The Physics of Virtual Processes is conceived

ANTIPARTICLES

e^+ ; \bar{p} , \bar{n} , $\bar{\Lambda}$, $\bar{\Sigma}$

1932

(Anderson, Blackett, Occhialini)

1955-57

(Segrè)(Piccioni)

ANTIMATTER

\bar{D} ; ${}^3\text{H}$, ${}^3\text{He}$, ✱④

1965

(CERN-Bologna)

1978-1980-1988

SPACE - AMS
1998 - 2010

1947

SUBNUCLEAR PHYSICS is born

$(2S_{1/2} - 2P_{1/2})$ Shift
(Lamb, Retherford)

Renormalization: 1947-71
Radiative Effects

1968

1968 ✱④

Scale Breaking in (DIS) \leftrightarrow (Scaling) \rightarrow (No Quarks)
All Quantities run with q^2 :
 $\alpha_1(q^2)$; $\alpha_2(q^2)$; $\alpha_3(q^2)$

Gauge Unification ✱⑤^a 1979-94
✱⑤^b and Gap

μ (2nd Family) lepton

✱②^a $(g-2)_\mu \equiv \text{QED}$ 1960

✱②^b $\tau_\mu \equiv G$ (Fermi) 1961

✱②^c HL \equiv 3rd Family 1960-1975

✱③^c 1968 $\Gamma(X^0 \rightarrow \gamma\gamma) \rightarrow \text{too small}$
 $\Gamma(X^0 \rightarrow \text{all}) \rightarrow \text{too high}$
 $m(X^0) \rightarrow \text{too high}$

1976 Instantons

η' -Leading in gluon Jets 1997 ✱③^o

π -Meson (1st Family) quarks
(Lattes, Occhialini, Powell)

$\pi \rightarrow \mu \rightarrow e$

$\pi^0 \rightarrow \gamma\gamma$

Nuclear Forces
 $R \approx 1$ Fermi
Why m_π so small?
(η - η') QCD (?)

V^0 -Particles (2nd Family) quark
(Blackett, Rochester, Butler)

$P \neq$

$C \neq$

1955

(θ - τ) puzzle

Flavour Mixing
& CP \neq

1957 LOY

CP \neq

1964

CP \neq

T \neq

?

Proliferation

Statics

Dynamics

SU(3)_f

1980 Effective Energy ✱③^a

New intrinsic
degree of freedom

Universality
Features ✱③^b

SU(3)_c \equiv QCD
Asymptotic freedom - Confinement
(1972-1974) (1975) ✱④

THE STANDARD MODEL

≥ 20 Parameters

SU(3)_c \otimes SU(2)_L \otimes U(1)_Y Repeated 3 times

QCD

QFD

QED

Mixing in Quark (1963) and Lepton (1997) Sectors

FROM FERMI-DIRAC TO NOW

1927

P.A.M. DIRAC

$$(i\not{\partial} + m)\psi = 0$$

The Physics of Virtual Processes is conceived

ANTIPARTICLES

e^+ ; \bar{p} , \bar{n} , $\bar{\Lambda}$, $\bar{\Sigma}$

1932

(Anderson, Blackett, Occhialini)

1955-57

(Segrè)(Piccioni)

ANTIMATTER

\bar{D} ; ${}^3\bar{H}$, ${}^3\bar{H}_e$,



1965

(CERN-Bologna)

1978-1980-1988

SPACE - AMS
1998 - 2010

1947

SUBNUCLEAR PHYSICS is born

1947**SUBNUCLEAR PHYSICS is born**

$(2S_{1/2} - 2P_{1/2})$ Shift
(Lamb, Retherford)

π -Meson (1st Family) quarks
(Lattes, Occhialini, Powell)

V^0 -Particles (2nd Family) quark
(Blackett, Rochester, Butler)

Renormalization: 1947-71
Radiative Effects

$\pi \rightarrow \mu \rightarrow e$

$\pi^0 \rightarrow \gamma\gamma$

$P \neq$
 $C \neq$
1955

($\theta - \tau$) puzzle

Flavour Mixing
& $CP \neq$
1957 | LOY

Proliferation

Scale Breaking in (DIS) (Scaling) (No Quarks)
All Quantities run with q^2 :
 $\alpha_1(q^2); \alpha_2(q^2); \alpha_3(q^2)$

Gauge Unification and Gap
(5^a) (5^b) **1979-94**

μ (2nd Family) lepton

Nuclear Forces
 $R \approx 1$ Fermi
Why m_π so small?
($\eta - \eta'$) QCD (?)

$CP \neq$
1964

$CP \neq$
 $T \neq$
?

Statics

Dynamics

$SU(3)_f$

1980 Effective Energy (3^a)

New intrinsic
degree of freedom

Universality
Features (3^b)

(2^a) (2^b) (2^c)
($g-2$) $_\mu \equiv$ QED **1960**
 $\tau_\mu \equiv G$ (Fermi) **1961**
HL \equiv 3rd Family **1960-1975**

(3^c) **1968**
 $\Gamma(X^0 \rightarrow \gamma\gamma) \rightarrow$ too small
 $\Gamma(X^0 \rightarrow \text{all}) \rightarrow$ too high
 $m(X^0) \rightarrow$ too high

1976 Instantons

η' -Leading in gluon Jets **1997** (3^d)

$SU(3)_c \equiv$ QCD
Asymptotic freedom – Confinement
(1972-1974) (1975) (4)

THE STANDARD MODEL

≈ 20 Parameters

$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ Repeated 3 times

QCD

QFD

QED

Mixing in Quark (**1963**) and Lepton (**1997**) Sectors

Mass \neq Matter

$$|m_i\rangle \equiv \text{Mass} \equiv \text{Antimass} \equiv |\bar{m}_i\rangle$$

$i \equiv 1$ (Intrinsic); $i \equiv 2$ (Confinement); $i \equiv 3$ (Binding)

$$C |m_i\rangle = |m_i\rangle \quad \boxed{***}$$

$$i \equiv 1, 2, 3$$

$$|m_i Q_j\rangle \equiv \text{Matter} \neq \text{Antimatter} \equiv |m_i \bar{Q}_j\rangle$$

$Q_j \equiv$ Flavour Charges

$$j \equiv (u \ d \ c \ s \ t \ b) \equiv (1, 2, 3, 4, 5, 6)$$

$$(\nu_e \ e^- \ \nu_\mu \ \mu^- \ \nu_{HL} \ HL^-) \equiv (7, 8, 9, 10, 11, 12)$$

$$\downarrow$$

$$\tau^-$$

$$C |m_i Q_j\rangle = |m_i \bar{Q}_j\rangle$$

$***$

$$i \equiv 1, 2, 3 ; J \equiv 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12.$$

Mass \neq Matter

$$|m_i\rangle \equiv \text{Mass} \equiv \text{Antimass} \equiv |\bar{m}_i\rangle$$

i \equiv **1** (Intrinsic); **i** \equiv **2** (Confinement); **i** \equiv **3** (Binding)

$$C |m_i\rangle = |m_i\rangle$$



$$\mathbf{i} \equiv \mathbf{1,2,3}$$

$$|m_i Q_j\rangle \equiv \text{Matter} \neq \text{Antimatter} \equiv |m_i \bar{Q}_j\rangle$$

$Q_j \equiv$ Flavour Charges

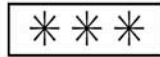
$$j \equiv (u \quad d \quad c \quad s \quad t \quad b) \equiv (1, 2, 3, 4, 5, 6)$$

$$(v_e \quad e^- \quad v_\mu \quad \mu^- \quad v_{HL} \quad HL^-) \equiv (7, 8, 9, 10, 11, 12)$$

$$\downarrow$$

$$\tau^-$$

$$C|m_iQ_j\rangle = |m_i\overline{Q}_j\rangle$$



$i \equiv 1, 2, 3$; $J \equiv 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12$.

Let me close
with the citation of Heisenberg, made
by T.D. Lee in Bologna, during his
opening lecture for the Symposium
celebrating the 30th Anniversary of the
Discovery of Antimatter (see Fig. 4).

T.D. Lee said:

«*in his book “The Physicist’s Conception of Nature” (1972), Werner Heisenberg writes: “I think that this discovery of antimatter was perhaps the biggest jump of all big jumps in physics in our century.”*»

Now, Heisenberg discovered quantum mechanics in 1925.

By 1972, he had witnessed almost all the big jumps in modern physics.

Yet he would rank the discovery of antimatter as the biggest jump of all».

REFERENCES

- [1] The Quantum Theory of the Electron
P.A.M. Dirac, *Proc. Roy. Soc. A*117, 610 (1928);
Quantised Singularities in the Electromagnetic Field
P.A.M. Dirac, *Proc. Roy. Soc. A*133, 60 (1931);
The Principles of Quantum Mechanics
P.A.M. Dirac, (4th edn), Clarendon Press, Oxford (1958).
- [2] *Are Matter and Antimatter Symmetric?*
T.D. Lee. Proceedings of the “Symposium to celebrate the 30th anniversary of the Discovery of Nuclear Antimatter”, L. Maiani and R.A. Ricci (eds), Conference Proceedings 53, page 1, Italian Physical Society, Bologna, Italy (1995).
- [3] *Gruppentheorie und Quantenmechanik*
H. Weyl, 2nd ed., 234 (1931).
- [4] *Unitary Representations of the Inhomogeneous Lorentz Group*
E.P. Wigner, *Ann. Math.*, 40, 149 (1939).
- [5] *Intrinsic Parity of Elementary Particles*
G.C. Wick, E.P. Wigner, and A.S. Wightman, *Phys. Rev.* 88, 101 (1952).

- [6] *Über die Operation der Zeitumkehr in der Quanten-mechanik*
E.P. Wigner, *Gött. Nach.* 31 546-559 (1932). Here for the first time an anti-unitary symmetry appears.
- [7] E.P. Wigner, *Ann. Math.* 40, 149 (1939).
- [8] J. Schwinger, *Phys. Rev.* 82, 914 (1951).
- [9] *Time Reversal in Field Theory*
J.S. Bell, *Proc. Roy. Soc. (London)* A231, 479-495 (1955).
- [10] *The Positive Electron*
C.D. Anderson, *Phys. Rev.* 43, 491 (1933);
- [11] *Some Photographs of the Tracks of Penetrating Radiation*
P.M.S. Blackett and G.P.S. Occhialini, *Proc. Roy. Soc.* A139, 699 (1933).
- [12] *Observation of Antiprotons*
O. Chamberlain, E. Segrè, C. Wiegand, and T. Ypsilantis, *Physical Review* 100, 947 (1955).
- [13] *Anti-Neutrons Produced from Anti-Protons in Charge Exchange Collisions*
B. Cork, G.R. Lambertson, O. Piccioni, W.A. Wenzel, *Physical Review* 104, 1193 (1957).

- [14] *Observation of Long-Lived Neutral V Particles*
K. Lande, E.T. Booth, J. Impeduglia, L.M. Lederman, and W. Chinowski, *Physical Review* 103, 1901 (1956).
- [15] *From the Yukawa Particle to the QGCW*
A. Zichichi, Opening Lecture of the Symposium for the Centennial Celebration of Hideki Yukawa, Proceedings of the International Nuclear Physics Conference, Tokyo, Japan, (2007).
- [16] *On the Analysis of τ -Meson data and the Nature of the τ -Meson*
R.H. Dalitz, *Phil. Mag.* 44, 1068 (1953);
Isotopic Spin Changes in τ and θ Decay
R.H. Dalitz, *Proceedings of the Physical Society* A69, 527 (1956);
Present Status of τ Spin-Parity
R.H. Dalitz, Proceedings of the “Sixth Annual Rochester Conference on High Energy Nuclear Physics”, Interscience Publishers, Inc., New York, 19 (1956); for a detailed record of the events which led to the (θ – τ) puzzle see R.H. Dalitz “Kaon Decays to Pions: the τ – θ Problem” in “History of Original Ideas and Basic Discoveries in Particle Physics”, H.B. Newman and T. Ypsilantis (eds), Plenum Press, New York and London, 163 (1994).
- [17] *Question of Parity Conservation in Weak Interactions*
T.D. Lee and C.N. Yang, *Phys. Rev.* 104, 254 (1956).

- [18] *Experimental Test of Parity Conservation in Beta Decay*
C.S. Wu, E. Ambler, R.W. Hayward, D.D. Hoppes, *Phys. Rev.* 105, 1413 (1957);
Observation of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: The Magnetic Moment of the Free Muon
R. Garwin, L. Lederman, and M. Weinrich, *Phys. Rev.* 105, 1415 (1957);
Nuclear Emulsion Evidence for Parity Non-Conservation in the Decay Chain $\pi^+\mu^+e^+$
J.J. Friedman and V.L. Telegdi, *Phys. Rev.* 105, 1681 (1957).
- [19] *On the Conservation Laws for Weak Interactions*
L.D. Landau, *Zh. Éksp. Teor. Fiz.* 32, 405 (1957).
- [20] *Evidence for the 2π Decay of the K_2^0 Meson*
J. Christenson, J.W. Cronin, V.L. Fitch, and R. Turlay, *Physical Review Letters* 113, 138 (1964).
- [21] *Remarks on Possible Noninvariance under Time Reversal and Charge Conjugation*
T.D. Lee, R. Oehme, and C.N. Yang, *Physical Review* 106, 340 (1957).
- [22] *Experimental Observation of Antideuteron Production*
T. Massam, Th. Muller, B. Righini, M. Schneegans, and A. Zichichi, *Nuovo Cimento* 39, 10 (1965).